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The 2011 Virginia Earthquake: What Are Scientists Learning?

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Nearly 1 year ago, on 23 August, tens of millions of people in the eastern United States and southeastern Canada were startled in the middle of their workday (1:51 P.M. local time) by the sudden onset of moderate to strong ground shaking from a rare magnitude (*M*) 5.8 earthquake in central Virginia. Treating the shaking as if it were a fire drill, millions of workers in Washington, D. C., New York City, and other eastern cities hurriedly exited their buildings, exposing themselves to potentially greater danger from falling bricks and glass; "drop, cover, and hold" would have been a better response. Fortunately, the strong shaking stopped after about 5 seconds and did not cause widespread severe damage or serious injuries.

The central Virginia earthquake, among the largest on the eastern seaboard during the approximately 400-year historic record, occurred as the result of reverse slip on a previously unrecognized north-to-northeast striking fault within the Central Virginia seismic zone (CVSZ) (Figure 1a). Many old faults are mapped in the CVSZ, yet no individual strands were previously confirmed to be active. However, persistent low-level seismicity has been observed during historical times, and instrumental recordings since about 1970 detect ongoing distributed seismicity within the CVSZ [*Bollinger and Hopper*, 1971], which has been identified by the U.S. Geological Survey (USGS) as an area of elevated earthquake hazard since 1976 [*Algermissen and Perkins*, 1976].

Moderate to large earthquakes in the eastern and central United States are rare, but their impacts can be extensive and severe. Fortunately, the 23 August 2011 earthquake was far enough from old buildings and the densely populated Richmond, Va., metropolitan area (about 65 kilometers away) that no lives were lost, and no serious damage was inflicted there. However, moderately heavy damage occurred to schools, businesses, and homes in rural Louisa County, southwest of Mineral, Va. Widespread light to moderate damage occurred from central Virginia to southern Maryland. Several national landmarks, including the Washington Monument and the Washington National Cathedral (Figure 1b) in Washington, D. C., approximately 135 kilometers away from the central Virginia epicenter, suffered damage.

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Central Virginia Earthquake: Source Parameters and Historical Perspective

The 23 August 2011 earthquake occurred at a relatively shallow depth of about 6 kilometers. Its moment tensor solution (Figure 1a) indicates a N28°E-striking nodal plane that dips down at 50° to the east-southeast, consistent with a plane well defined by aftershocks and reverse (southeast-side-up) motion. The earthquake occurred in multiply deformed metamorphic rocks of the Appalachian Piedmont and within thrust sheets imaged on a

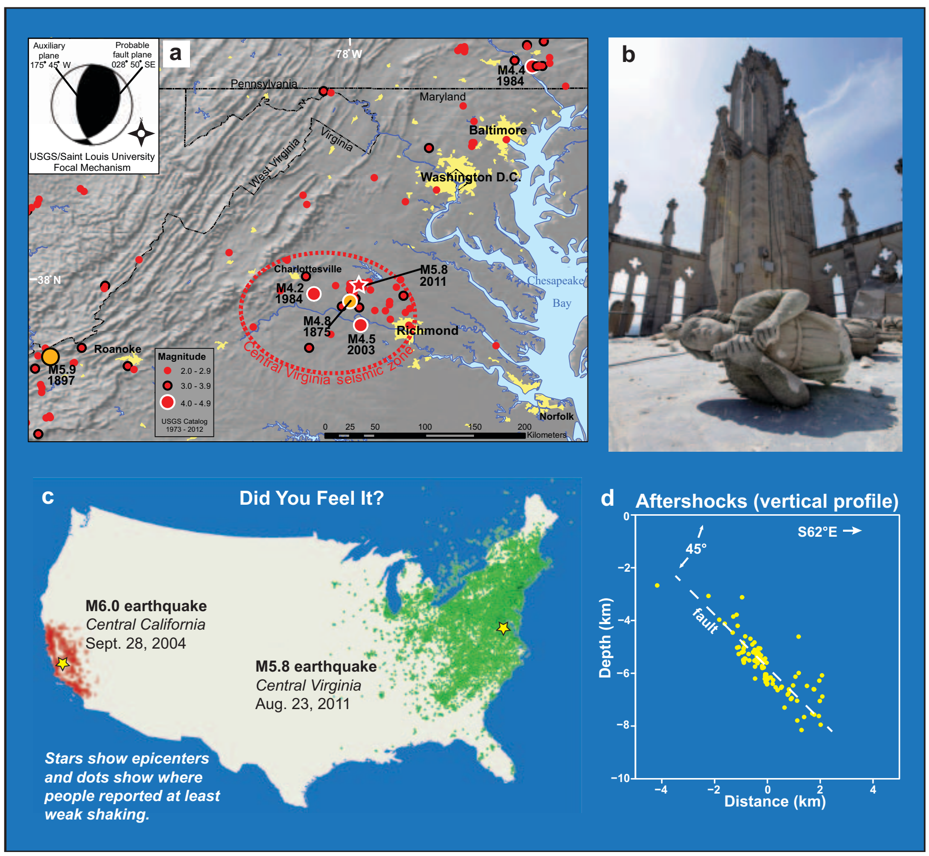

Fig. 1. (a) The M *= 5.8 earthquake in the Central Virginia seismic zone has a moment tensor solution (http://earthquake.usgs.gov) indicating reverse motion on an east-southeast-dipping plane consistent with aftershocks. (b) Damage to buildings such as the Washington National Cathedral in Washington, D. C., 135 kilometers northeast of the central Virginia epicenter, is a reminder that engineered structures in eastern North American cities are vulnerable under moderate shaking (photo by J. Scott Applewhite, Associated Press). (c) U.S. Geological Survey "Did You Feel It?" data from the* M *= 5.8 Virginia earthquake (green) and from one of similar magnitude and depth in California (red) illustrate how earthquakes are felt over much larger areas in the eastern United States than those west of the Rocky Mountains. (d) Virginia aftershocks define an east-southeast-dipping fault rupture plane.*

USGS seismic reflection profile [*Pratt et al.*, 1988].

This may be the largest earthquake to strike the central and eastern United States since the $M = 5.8$ earthquake near Cornwall and Massena, N. Y., in 1944. The previous largest earthquake in the region was the approximately $M = 5.9$ Giles County earthquake in southwest Virginia in 1897. A recent review of intensity surveys for the 1897 earthquake, however, suggests that it was smaller, about $M = 5.5$ [*Hough*, 2012]. In 1875 an $M = 4.8$ earthquake in the CVSZ (strongly felt in Richmond) shook bricks from chimneys, broke plaster and windows, and overturned furniture at several locations. In December 2003 an $M = 4.5$ earthquake in the CVSZ produced only minor damage. The historical and instrumental seismicity in the CVSZ prior to this event was distributed broadly over most of the zone without obvious trends.

Rapid Scientific Response

About 148,000 people reported their experiences with the 23 August earthquake on the USGS "Did You Feel It?" Web site; this number of responses is more than for any other earthquake since the Web site came online. Reports came from Maine to Florida along the eastern seaboard, and west to Chicago and western Tennessee. Shaking was reported from an area occupied by a third of the U.S. population (Figure 1c). Because of differences in crustal rock properties, earthquakes east of the Rocky Mountains are felt over much larger areas than those to the west. Figure 1c provides an example of this difference by comparing "Did You Feel It?" maps for this earthquake and one of similar magnitude and depth in California. It is reasonable to conclude that more people felt this earthquake than any other in U.S. history.

Immediately following the main shock, multiple institutions including USGS, Virginia Polytechnic Institute and State University (Virginia Tech), Lamont-Doherty Earth Observatory of Columbia University, University of Memphis Center for Earthquake Research and Information, Lehigh University, Incorporated Research Institutions for Seismology, and Cornell University deployed seismic equipment in the source region. More than 40 three-component seismographs were deployed within 5 days, and eight of these were installed within 24 hours, just in time to record the largest aftershock ($M = 3.9$) on 25 August. More than 200 single-component recorders were added by 1 September for an experiment in aftershock imaging with dense arrays (http://www.iris.edu/hq/iris_workshop2012/scihi/WebPages/0064.html). About 35 seismographs remained in the area through early 2012, and several are in place a year after the event.

All together, these efforts yielded the best recorded aftershock sequence in the eastern United States. Aftershock monitoring is valuable for locating and characterizing the dimensions of the causative fault, recording data useful for ground motion investigations, and characterizing the aftershock-sequence decay rate. Knowing the number, size, and timing of aftershocks could help in predicting the characteristics of future aftershock sequences in eastern North America.

In addition to aftershock monitoring, crews from USGS, the Virginia Division of Geology and Mineral Resources, Virginia Tech, and the Earthquake Engineering Research Institute (http://www.eqclearinghouse.org/2011-08-23-virginia/) arrived within 24 hours of the main shock to begin systematic damage assessments and reconnaissance for surface fault rupture and seismically induced ground failure. No evidence for surface rupture was found, but two small sand boils caused by seismic liquefaction were found within a few kilometers of the epicenter, and rock falls occurred throughout the region as far from the epicenter as Maryland [*Jibson and Harp*, 2012].

USGS well monitoring recorded changes in groundwater levels in at least 48 wells, located as far as 560 kilometers from the epicenter, within minutes to 24 hours after the main shock [*Roeloffs et al.*, 2011]. The maximum water level change recorded was 65 centimeters in a well in Pennsylvania, although most changes were less than 15 centimeters (rise and fall).

Earthquake Effects and Aftershocks: What Have We Learned a Year Later?

Assessments of USGS "Did You Feel It?" intensity data from this event support previous interpretations that seismic energy from eastern seaboard earthquakes can have pronounced asymmetry. An asymmetric distribution of Mercalli intensities from this earthquake, consistent with the elongate felt area in Figure 1c, suggests anisotropic wave propagation due to the prevailing northeasterly tectonic fabric, which in this case could have directed more seismic energy toward Washington, D. C., and New York [*Hough*, 2012]. However, the mechanisms for explaining asymmetric intensities and the significance of material anisotropy for wave propagation need scientific study. *Jibson and Harp* [2012] found rock falls up to 250 kilometers from the epicenter, especially to the southwest and northeast. This observation contrasts with western U.S. sites, where rock falls triggered by an $M = 5.8$ earthquake would be expected only up to about 70 kilometers from the epicenter.

Structural damage to buildings was asymmetric around the epicenter, and brick buildings and other unreinforced masonry performed poorly. Damage in Louisa County alone is estimated to be more than $80 million [*Dennen*, 2011]. Damage to the Washington Monument (still closed for repairs) and the Washington National Cathedral could cost $40 million to repair [*Raasch*, 2012]. The safe shutdown of the North Anna nuclear power station due to readings from strong ground motion sensors at the station, located 18 kilometers northeast of the epicenter, lasted 2.5 months after operating basis and design basis acceleration criteria were exceeded for certain directions and frequencies; this was the first time an operating nuclear power plant in the United States shut down in response to an earthquake [*Bacqué and Martz*, 2011; *Fenster and Walsh*, 2011].

Aftershocks greater than $M = 1.8$ reported by USGS and others indicate a 10-kilometer-long fault rupture plane that strikes about N30°E and dips down to the east-southeast at approximately 45 degrees [*Ellsworth et al.*, 2011] (Figure 1d). To the knowledge of the authors, this is the first time an eastern U.S. earthquake can be unequivocally associated with a causal fault based on modern instrumental data. Aftershock focal depths span a range of 2–8 kilometers. USGS reports at least 450 aftershocks greater than about $M = 1.0$; none of these were greater than $M = 4.0$, and only about 6 were $M = 3.0$ to $M = 3.9$. Earthquakes with magnitudes between 0.5 and 1.0 have not yet been fully tallied but likely number in the hundreds. The aftershock sequence is decaying, and only a few earthquakes with magnitudes between 1.7 and 2.4 have occurred in the zone since 2 May 2012. With few earthquakes as large as $M = 5.8$ recorded in the eastern United States, it is difficult to know what is normal, yet an aftershock of about $M = 4.5$ is still possible over the next few months.

Looking Ahead

Considerable scientific uncertainty remains about the nature and scope of the earthquake hazard associated with the CVSZ and similar zones in eastern North America. Research is under way to better understand the geological and geophysical setting of the August 2011 earthquake and the severity and distribution of seismic shaking, including the geologic characteristics of seismic recording sites, the characteristics of the earthquake source, and associated ground deformation and failures. New airborne geophysical surveys are collecting lidar, magnetic, gravity, and radiometric data in the epicentral region, and when combined with additional geologic fieldwork, scientists hope to develop an improved understanding of earthquake hazard along the eastern seaboard. Infrequent large earthquakes and sparse evidence of Quaternary (~2.6 million years ago to the present) earthquake history in the eastern United States point to the importance of investigating this rare earthquake to develop scientific insights necessary to improve seismic hazard assessment in the region.

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